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The Sagavanirktok River, North Slope Alaska: Characterization of an Arctic Stream

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ABSTRACT

The Sagavanirktok River is the second largest river on the Alaskan North Slope, draining approximately 14,890 km^2 of the Central and Eastern Brooks Range into the Beaufort Sea. Even though discovery of oil in Prudhoe Bay has focused attention on the river since the late 1960's, few quantitative studies have been conducted. This makes description of the stream channel, and analysis of the streamflow and sediment load under its distinctive climatic conditions quite difficult.

The climate plays a large role in characterizing the Sagavanirktok River. Winter lasts from 8 to 9 months in this high latitude "desert" environment. The North Slope receives low annual precipitation, only 10 to 15 cm near the coast and 50 to 100 cm inland, although there are areas in the high Arctic with substantially lower precipitation. Permafrost extends to a depth of 650 m, but in the summer the surface may thaw up to 2 m in depth. In the winter, the active layer is completely frozen, and streamflow is effectively eliminated as streams are frozen. Break-up of the frozen streams occurs in late May and freeze-up occurs in late September.

At-a-station hydraulic geometry studies were performed using information obtained from USGS WRD gaging stations. At the Sagwon station, these yielded best-fit line slope values of b=0.06, f=0.46 and m=0.47 for plots of width, depth and velocity versus discharge, respectively. At the Atigun tributary station, these yielded best-fit line slope values of b=0.13, f=0.17 and m=0.63. These values are similar to average exponent values obtained using similar data sets at other streams in the United States. Limited data from at-a-station hydraulic geometry studies at the four distributary locations yielded inconclusive results. Therefore, downstream changes in hydraulic geometry could not be determined. Channel geometry studies indicated an increase in the bankfull width/depth ratio with distance downstream.

Bedload sediment transport calculations based on hydrologic data from the Sagwon gaging station and the four distributary channels were performed. At the Sagwon station the boundary shear stress (T_B)=625 dynes/cm^2, the median particle diameter (D_{50})=65 mm, and the bedload sediment transport rate (Q_S)=0.26 tons/year per km^2 of drainage area. At the studied distributary channels, T_B=86 to 146 dynes/cm^2, D_{50}=15 mm and Q_S=0. These calculations were in keeping with observations noted in previous studies of the river, but are lower than Milliman and Meade's estimate of suspended sediment yield for North Alaskan streams since bedload is usually quite low in any stream compared to the suspended sediment load. Suspended load increased with increase in discharge.

Arctic streams are characterized by the presence of three additional elements: 1) permafrost, perennially frozen ground; 2) icings, large masses of ice; and 3) frazil ice/anchor ice, slushy ice which forms in supercooled waters. The latter two may be additional agents of sediment transport.

INTRODUCTION

Description of the Problem:

The Sagavanirktok River is the second largest river on the North Slope of Alaska, draining approximately 14,890 km^2 of the eastern Brooks Range into the Beaufort Sea (Figure 1). Very little was known about the North Slope until the 1940's when it became the focus of attention as a possible oil producing area. In the late 1960's, the discovery of oil reserves at the mouth of one of the Sagavanirktok's distributaries near Prudhoe Bay resulted in exploration activities focused in the

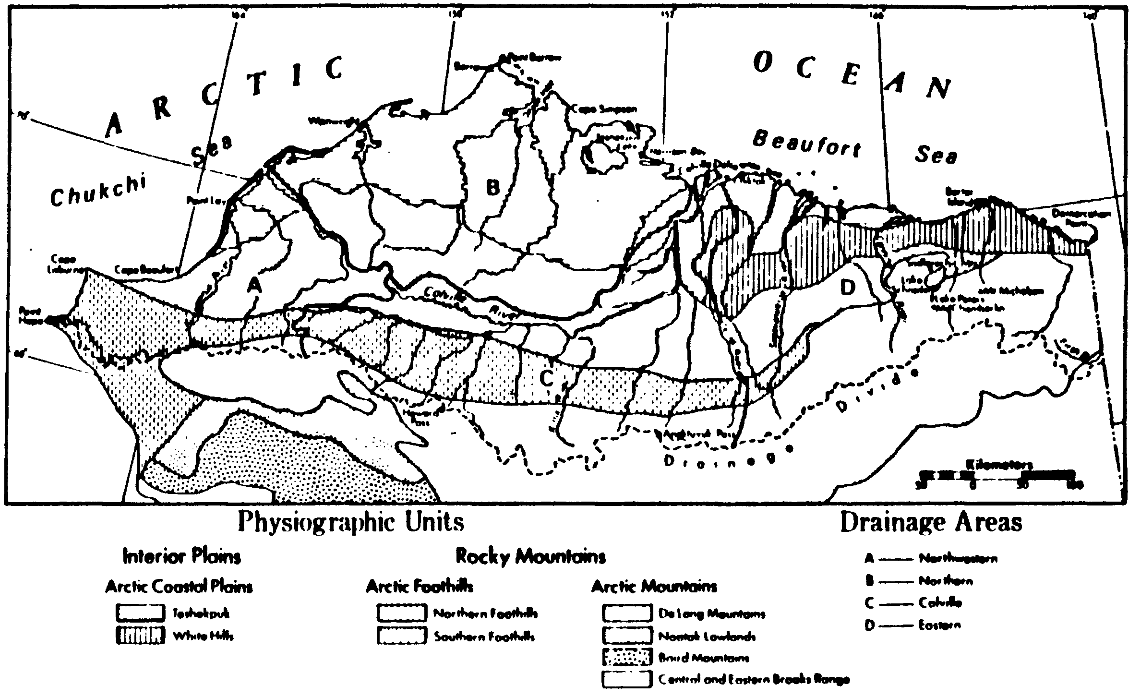


FIGURE 1 Physiographic provinces, drainage regions, and key locations of the North Slope. (From Walker, 1973)

Sagavanirktok delta area. Most of these studies concentrated more on stratigraphy and structural geology than on river processes. Extensive hydrologic data has been collected at only two gaging stations: near Sagwon, approximately 150 km (90 mi) upstream from the delta, and at the Atigun River tributary near Pump Station 4. Data has also been obtained at several other reaches along the river for one or two field seasons during private firm and government agency investigations. Such limited information makes long term study of the river difficult. This report uses the limited available data to describe the stream channel and analyze the streamflow and sediment bedload under distinctive climatic conditions.

Scope of Investigation:

Of the limited data available for the Sagavanirktok River, four studies proved most useful. The first two involved information obtained from United States Geological Survey Water Resources Division (USGS WRD) stream gaging stations. In 1969, a gaging station was installed near Sagwon, located approximately 1 km (0.6 mi) downstream from the intersection with the Lupine River (Figure 2). During 1969 and 1970, only crest gage readings were taken. In 1971, a water level recorder was installed and periodic discharge measurements were made, so that average daily discharge could be calculated. During the first several years, surveys of three cross-sections were conducted immediately upstream from the gage. Occupation of the Sagwon gaging station was terminated after the 1978 water year (October 1977 through September 1978). The second station, which was installed on a tributary of the Atigun River also had a water level recorder and was used from 1976 through 1983 (Figure 2).

The third study was conducted by Scott (1978) and involved information obtained from a number of stations along the Sagavanirktok River during the 1976 and 1977 spring ice break-up seasons. Data collected included size of drainage area, median diameter of bed material (D_{50}), channel slope, and channel pattern (Figure 2 and Table 1). Although Scott's focus was on the effects of permafrost (perennially frozen ground) on river channel behavior, and included little in the way of hydrologic information, his data was of great help in obtaining indirect calculations of bedload transport.

The fourth study was conducted by two private research firms, Hydrocon Engineering and Woodward-Clyde, for water years 1981 and 1982 (Ecological Research Associates, 1982). They concentrated on four of the Sagavanirktok distributaries. The available data, involving cross-sectional surveys, mean daily discharge measurements, and suspended sediment concentration, was combined with data from the Sagwon gaging station in order to classify the hydrology and the sediment transport of the Sagavanirktok River.

DESCRIPTION OF STUDY AREA

General Location:

Northern Alaska can be divided into three distinct physiographic provinces (Wahrhaftig, 1965). The Brooks Range province consists of a large chain of east-west trending mountains of high relief. North of this province lies the Arctic foothill province, and still northward lies the low-relief Arctic coastal plains province (Figure 1). A number of rivers drain sequences of marine and continental sedimentary rocks on the northern side of the Brooks Range. The Colville River is the largest river on the North Slope with a total drainage area of approximately 50,000 km^2 (19,305 mi^2) and a length of nearly 600 km (373 mi) (Arnborg et al., 1966 and Arnborg et al., 1967). The Sagavanirktok is the second largest river. Its total drainage area is approximately 14,892 km^2 (5,750 mi^2) and its length is nearly 267 km (166 mi) (Boothroyd and Timson,1983). Since the Trans Alaska Pipeline route and haul road closely parallel the Sagavanirktok River for much of its length, it is the most easily accessible river on the North Slope.

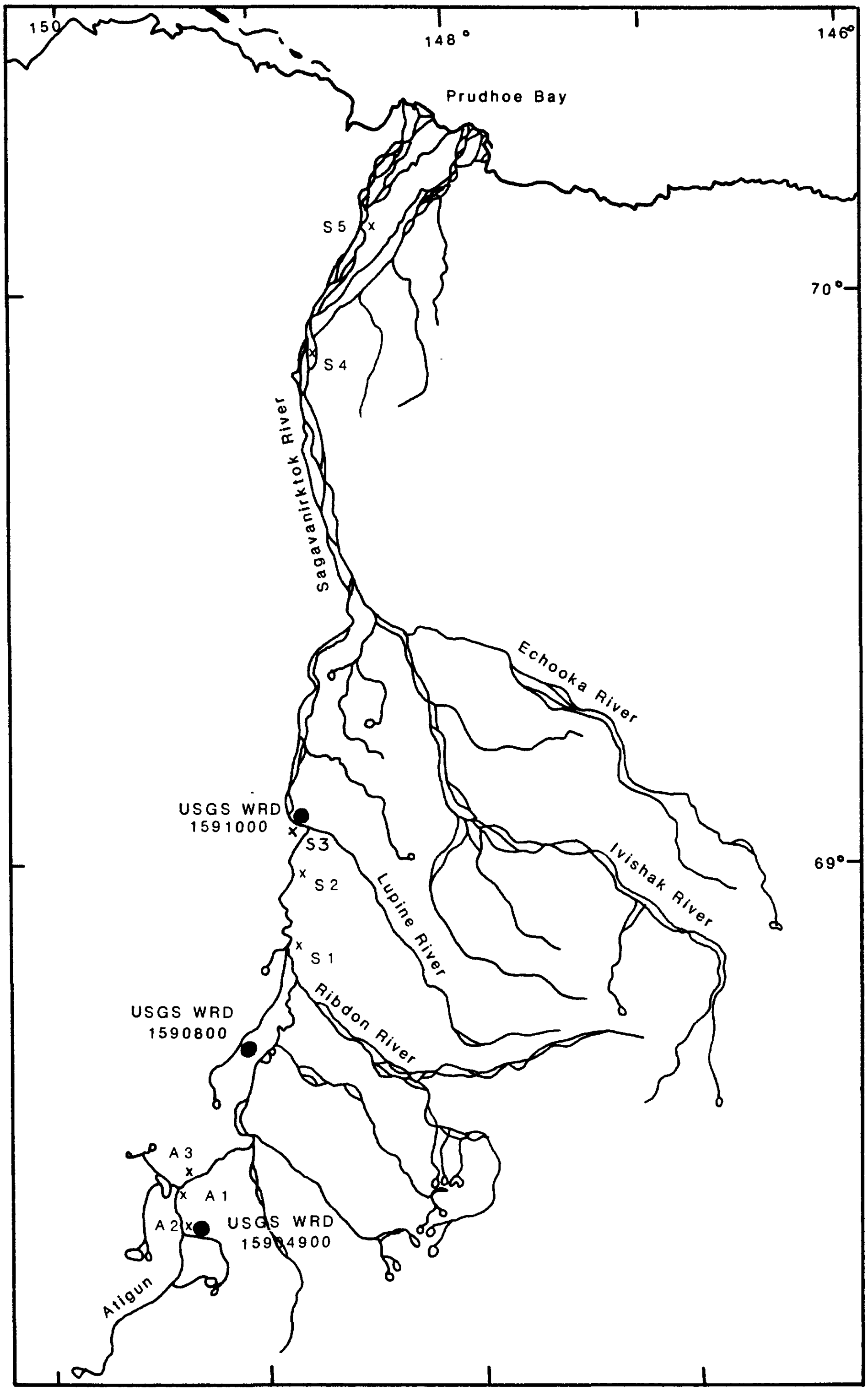


FIGURE 2 Sagavanirktok USGS WRD water gaging stations and Scott's (1978) sample site locations (A1-A3 and S1-S5).

TABLE 1

Scott's characteristics of the Sagavanirktok and Atigun Rivers at sites shown in Figure 3 (modified from Scott, 1978).

Stream	Site No.	Drainage Area (km^2)	Median Diameter of Bed Material (mm)	Channel Slope (m/m)
Sagavanirktok	S1	4,680	80	0.0032
	S2	4,830	86	0.0023
	S3	5.870	45	0.0025
	S4	12,200	18	0.0018
	S5	*	15	0.00053
Atigun River	A1	435	22	0.00088
	A2	600	0.41	0.001
	A3	760	0.38	0.001

* Distributary

North Slope Topography:

Most of the drainage basin of the Sagavanirktok River lies in the Arctic Foothill and Arctic Coastal Plain provinces, although several of its tributary headwaters are situated high in the mountainous territory of the Brooks Range (Scott, 1978). Along the river, there is an abrupt decline in slope as the river leaves the highly resistant Paleozoic rocks of the mountains and crosses the less resistant Mesozoic and Cenozoic rocks of the foothills (Keller et al., 1961).

According to Boothroyd and Timson (1983), many of the North Slope rivers cut down into the underlying rocks of the foothill belt during the Quaternary and produced long, low hills which are located between the current river course and abandoned courses. These remnant features may be as long as 100 km (60 mi) and 200 m (650 ft) in relief. They are often flanked by abandoned flood plains and fluvial terraces of Pleistocene age, which are lower than the remnants, but some 20 to 60 m (60 to 180 ft) higher than the active river beds.

Geology:

Keller et al. (1961) have written a very detailed description of the stratigraphy of the Sagavanirktok River region. For the scope of this study, it is sufficient to say that the river drains an area of predominantly marine sedimentary rocks. These sedimentary rocks occur in stratigraphic belts, trending east-west and decreasing in age, northward from the Brooks Range to the Arctic Ocean (Figure 3). These older sedimentary rocks are overlain by scattered Quaternary deposits of the Gubik Formation (Beikman and Lathram, 1976). Glacial deposits may also be found in the upper reaches of the Sagavanirktok basin.

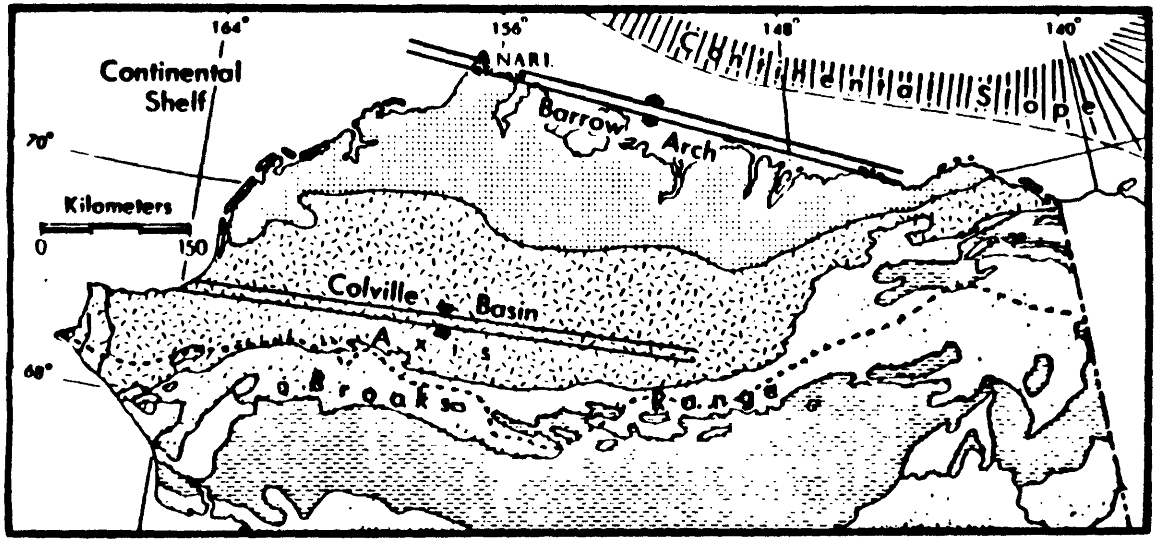
Climate:

Because of its high latitude position, winter on the North Slope lasts from eight to nine months out of the year. During this time, the low temperatures freeze all surface materials, and snow blankets the area. Summer is the next longest season, in which temperatures rarely drop below freezing. Spring and fall act as short transitional seasons, in which thawing and freezing are, respectively, frequent events (Walker, 1973).

From mid-April to the end of August, the sun remains above the horizon in this high latitude environment. Direct radiation from the sun aids in the relatively rapid break-up of ice on the frozen streams and helps to melt a shallow active layer in the perennially frozen ground.

Winter temperatures vary with distance from the ocean, but are between -30 and -40 ^{o}C at inland locations, and between -26 and -35 ^{o}C near the coast. Summer temperatures are between 10 and 18 ^{o}C inland and 5 to 13 ^{o}C near the coast (Scott, 1978).

Mean annual precipitation is generally from 10 to 15 cm (4 to 6 in) over most of the coastal plain, and rises with increasing altitude to 50 to 100 cm (20 to 40 in) in the upper reaches of the Brooks Range. Nearly half of this precipitation occurs as snowfall from September through May. Because of the sparse amount of precipitation, this virtually treeless area on the northern slope of the Brooks Range is often classified as a high latitude desert. Snow may fall in any month, but rain occurs in the summer months, and is associated with an oscillating semi-permanent arctic front which exists between the Arctic Ocean and the Brooks Range (Scott, 1978). Prevailing winds, strong at the coast and decreasing inland, are predominantly from the northeast (Keller, et al., 1961).



Quaternary Deposits on Mesozoic Basement

Successor Basin Deposits Late Mesozoic Sedimentary Rocks

Geosynclinal Deposits Mid-Paleozoic to Mid-Mesozoic Mainly Sedimentary Rocks

Drainage Divide

Older Geosynclinal Deposits Sedimentary and Metamorphic Rocks

Plutonic Rocks Paleozoic and Mesozoic

Thick Sedimentary Deposits Tertiary an Quaternary

FIGURE 3--North Slope geology (From Walker, 1973)

STREAMFLOW AND SEDIMENT TRANSPORT

Introduction to Hydrology:

The hydrology of the North Slope is heavily influenced by the arctic climate. Because of the dramatic variation in the amount of solar radiation received through the year, the area is subjected to eight to nine months of sub-freezing temperatures. These low temperatures result in a thick layer of permafrost. The permafrost may thaw to a depth of 0.5 m (2 ft) during the short summer period. Since much of the runoff into the streams is a result of thaw and the subsequent flow of groundwater through the active layer of the permafrost, the sub-freezing temperatures during the long winter months serve to prevent contribution of runoff to streamflow in all but a few sites where perennial springs are found to flow. These temperatures also serve to freeze the rivers, so that streamflow during much of the year is very low or non-existent. This means that the majority of the annual flow is concentrated in a relatively short period of time (Walker, 1974). This concentration of streamflow activity, thus confines the time available for sediment movement into an even smaller fraction of the year.

The streamflow period begins when the sun remains above the horizon, facilitating melting and break-up. The break-up period generally begins in late-May when the water first begins to appear on the icy surface of the stream. Over the next few days, the water accumulates to a depth of 1 m (3 ft) before it begins to flow on the surface (Arnborg et al., 1966). When the ice first begins to melt, it is free of sediment, but as flow is initiated and increases, the amount of sediment contributed from hillslope runoff builds on the icy surface, eventually covering it. During these first stages, water is unable to seep under the ice, but as fractures develop, seepage is common. Large pieces of bottom ice eventually float to the surface bringing with them adhering stream-bottom sediments (Arnborg et al., 1966). Break-up begins in the upper reaches of the river and its tributaries because this zone is warmer and more sunny. Along the Colville River, the break-up front proceeds northward at the rate of 0.5 to 0.8 km per hour (0.3 to 0.5 mph) (Drage et al., 1983). A similar rate of break-up along the Sagavanirktok River would be expected. Break-up generally lasts less than two days along any one stretch of the river (Arnborg et al., 1966).

Additional Arctic Stream Processes:

Northward drainage of the Brooks Range is greatly influenced by three major elements which characterize arctic streams: 1) permafrost, perennially frozen ground; 2) icings, large masses of ice; and 3) frazil ice, slushy ice which forms due to supercooled water temperatures.

Permafrost

The North Slope is underlain by some 650 m (2,100 ft) of continuous permafrost (Boothroyd et al., 1983) in which a shallow active layer, or zone of thaw, forms during the summer season. The thickness of the active layer is dependent on the type of surficial deposits, and the amount of solar radiation and vegetation. It may be only 0.3 m (1 ft) thick in cohesive tundra-covered material and as much as 2.0 m (6.5 ft) thick in non-cohesive unvegetated areas (Scott, 1978). The presence of permafrost can act as an effective barrier to water infiltration, thus allowing streamflow to run off more rapidly than in areas without underlying permafrost (Slaughter et al., 1983). Permafrost has also been determined to increase the yield of suspended sediment within a catchment area (Slaughter et al., 1983). This implies that a permafrost-dominated stream, which may have lower base-flow sediment yields, will also have a greater peak streamflow and larger concentrations of suspended sediment at peak flow periods, than rivers which are not underlain by permafrost (Slaughter et al., 1983).

Stream erosion is also influenced by the presence of permafrost. Rates of bank erosion are variable depending on bank height, composition, and exposure to erosional processes (Walker, 1983). Thermo-erosional niching, or bank-undercutting, is the dominant process behind bank retreat in cohesive material. This process is more rapid in sandy or gravelly materials. The bank's response to undercutting is to slump into the active river channel. Breakage points commonly occur along the edges of ice polygons formed in response to the thaw of permafrosted ground. If the bank materials are composed of peat or other vegetative mats, the slumping is lessened or retarded (Scott, 1978).

Permafrost may provide protection to some banks in the beginning of the break-up period, or towards the fall freeze-up, by acting as a cement for the unconsolidated materials. After the break-up peak, the high moisture content of the thawed material may serve to enhance bank erosion (Scott, 1978).

Icings

A second important characteristic of arctic streams is the production of icings, large bodies of ice which form when water from a river, a spring, or the ground seeps onto a land or ice surface during periods of sub-freezing temperatures, creating layer upon layer of ice (Carey, 1973). This phenomenon has been studied most extensively on the Sagavanirktok River, but has been recognized elsewhere. The larger icings, some miles in length, can be observed from year to year, since they commonly form at the same locations along the river, and frequently have the same size and shape (Harden et al., 1977). However, the smaller icings are varied in size and shape, and in some winters are not formed at all, depending on various hydrologic and meteorologic conditions (Sloan, 1976).

River ice begins to form during September, when the mean daily air temperature is below freezing. By December, the ice is generally several feet thick and the permafrost active layer is all but frozen solid. The river ice and frozen ground may act as barriers to flowing water, especially when the thickness of the ice canopy approaches the channel depth, and in this manner may force the flow to the surface. Continued overflowing of water causes a building up of sheets of ice covering the original frozen surface (Harden et al., 1977). Icing thickness may also be increased by water beneath the surface, freezing to the icy underside.

There is a documented correspondence between the formation of river icings and the presence of perennial springs located directly upstream from these icings. Many springs occur in the Sagavanirktok tributary basins. The Echooka springs supply fresh water to one of the largest icings in all Alaska. In May of 1973, these springs supplied an additional 110 cfs to the amount of discharge. Other sources located in the Sagavanirktok tributaries include springs along the Saviukviayak River, Flood Creek, and the Ivishak River. It has been estimated that between the Saviukviayak River and Flood Creek springs, the amount of water contained in these icings is equivalent to an annual yield of almost 0.3m (1 ft) of water over the two basins. Since the annual precipitation for this upstream area is from 0.5 to 1.0 m (1.5 to 3.0 ft), this groundwater discharge plays a sizeable role in the hydrology of the Sagavanirktok River region (Childers et al., 1977). Because water is stored in the icings, downstream streamflow is initially reduced (Sloan et al., 1976).

Some controversy exists as to whether the morphology of the North Slope plays a large role in the formation of icings, or vice versa. Because braided streams tend to be shallow, and cross-sectional freezing is faster here than in deeper reaches, thick flood-plain icings are common (Sloan et al., 1976). But the icings themselves, especially during the increased stage period of the spring and summer flooding, may cause lateral migration and/or downcutting as the flow is diverted around ice blocks. Braided stream patterns may then become a product of the icing formation (Harden et al., 1977).

Frazil Ice

Another important characteristic of the arctic streams is the formation of frazil ice, small discs of ice which have diameters of approximately 1 to 4 mm and thicknesses of 1 to 100 microns. This ice is formed in supercooled turbulent waters (Kvisigild, 1970). The frazil ice not only affects river hydrology by increasing the stage, or water elevation, and decreasing the velocity, but it also appears to play an active role in sediment transportation. Such ice begins to form in the Arctic by September (Martin, 1981).

Studies on the Niagra River and in Sweden confirm that the formation of frazil ice in open waters occurs when the surface water temperature drops to 0.01 to 0.1^{o} C below freezing. This commonly occurs when wind and an absence of direct solar radiation combine to produce radiative cooling (Martin, 1981). The formation cannot occur spontaneously, but must be initiated by a seeding process, such as the introduction of a single ice crystal from the atmosphere or riverbanks. Air samples taken above arctic streams were found to contain many ice crystals which could provide this seeding source (Osterkamp, 1977). After a single crystal is introduced into the turbulent supercooled water, a process referred to as "collision breeding" takes place, in which the number of ice crystals increases dramatically. The crystals do not tend to remain separate, but usually sinter together to form "flocs" which are 3 to 10 mm in width (Martin, 1981). At first, when only the surface waters have become supercooled, the crystals are often drawn into suspension, where they melt in the warmer waters below. The rate of frazil ice production increases as the body of water becomes progressively supercooled. Underwater observations have led some researchers to compare frazil ice to a "driving snow storm, as seen through the headlight beams of a moving automobile at night" (Arden and Wigle, 1973). When the entire river becomes supercooled, the ice becomes sticky and attaches itself to other crystals and also to sediment along the river bottom. Particles which are capable of being picked up are carried by the ice. If the particles are too large, the ice attaches itself to the bottom, forming what is known as "anchor ice" (Martin, 1981). If enough anchor ice builds up, it may be capable of transporting large boulders. This has been observed in Sweden, where ice and ice-carried rocks, some of which weigh as much as 30 kg, have caused many problems for their hydro-electric plants (Martin, 1981).

Ice, as a mode of sediment transport, in both rivers and the open ocean, has been observed with underwater cameras. Further evidence includes the floating slush, which contains entrained sediment, and is due to the release of anchor ice as the sun heats up the body of water (Martin, 1981).

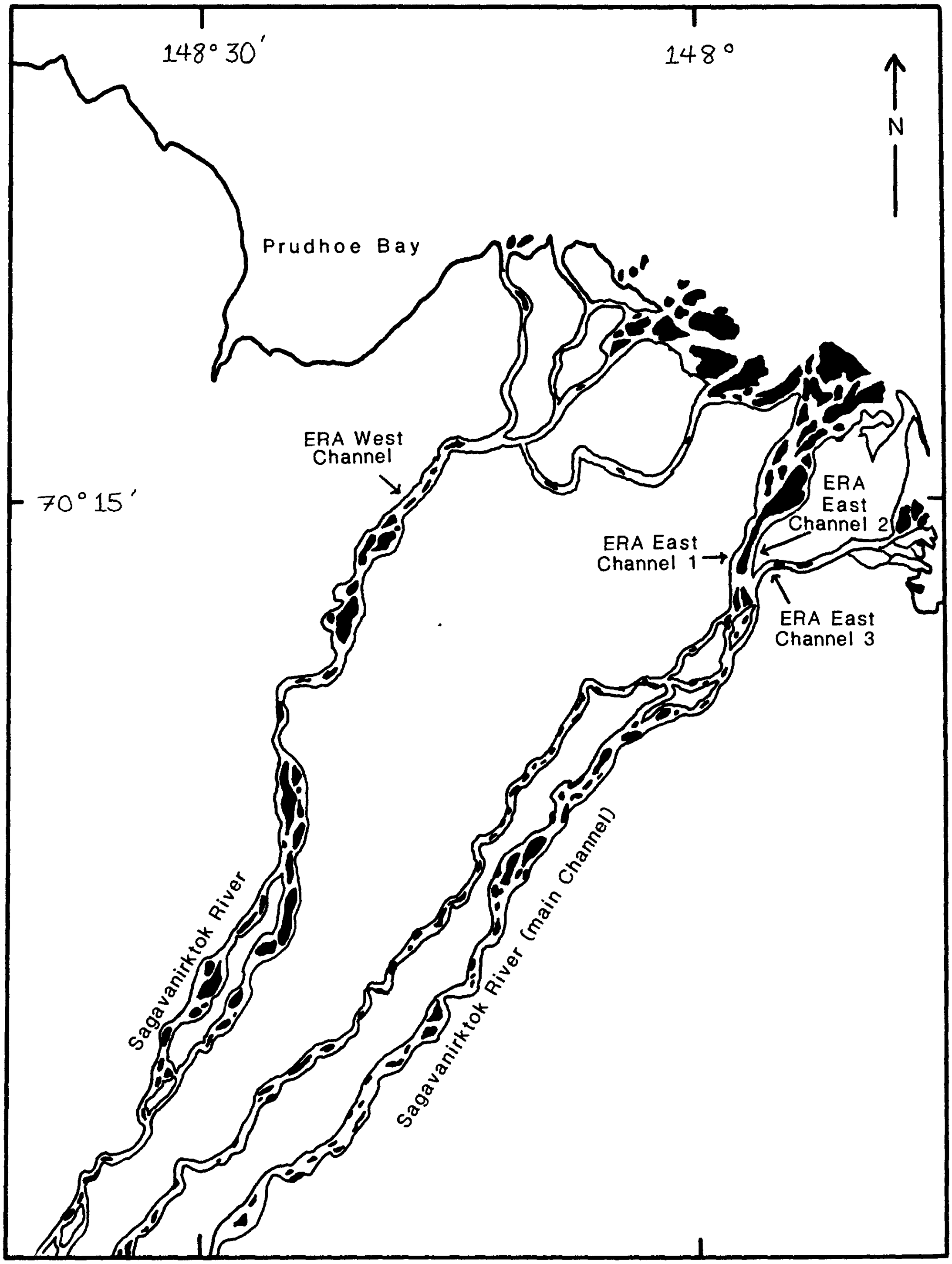
Collection and Analysis of Streamflow Data:

Hydrologic data from the Sagavanirktok River consists of USGS WRD gaging information from the Sagwon and Atigun tributary stations and the hydrologic investigations of Ecological Research Associates. Daily peak discharges at the Atigun tributary station were highest in 1976 (28.3 m^3/s or 1,000 cfs) and lowest in 1978 (11.5 m^3/s or 407 cfs). Daily peak discharges at the Sagwon station were highest in 1969 (988 m^3/s or 34,900 cfs) and lowest in 1975 (236 m^3/s or 8,340 cfs).

Until 1981, no detailed information of streamflow at the distributaries was available. In 1981 and 1982, two private consulting firms conducted a limited hydrologic study of four of the main distributary channels (Figure 4) which they named East Channels 1, 2 and 3, and West Channel (Ecological Research Associates, 1982). Maximum peak discharges for East Channels 1, 2 and 3 and for the West Channel were 67 m^3/s (2,373 cfs), 153 m^3/s (5,400 cfs), 23 m^3/s (812 cfs), and 236 m^3/s (8,335 cfs), respectively. No information on minimum discharges was available for any of these channels except the East Channel 3, which had no flow past September 15. Comparison with the Colville delta suggests that no fresh water reaches the ocean for several months, because the channels are completely frozen (Walker, 1974). ERA has estimated that between late May and late June, the period between break-up and peak flow, the West Channel carries approximately 49% of the total flow. The remainder consists of 5% for East Channel 3, and 46% combined total for East Channels 1 and 2. During July and August, the West Channel carries approximately 68 to 70% of the flow and East Channels 1 and 2 carry the remaining amount.

Hydraulic Geometry:

Streamflow data may be used in the determination of hydraulic geometry, in order to characterize natural stream channels. The channels are shaped by the amount of water and sediment that they carry. The changes in values of mean surface width (W), mean depth (D), and mean velocity (V), with changes in mean discharge (Q), may be used to show the hydraulic characteristics at a cross-section. These may then be compared with each other to determine if rivers in similar areas have similar hydraulic geometry.



Hydrologic sampling station locations (modified from Ecological Research Assoc., 1982).

FIGURE 4

One simple way of reconstructing the hydraulic geometry at a cross-section along the river is to use the information supplied by the USGS's Water Resources Division on their 9-207 forms. In addition to the daily mean discharge information collected at a USGS gaging station, there are sets of field notes which record W, D, V, and Q at various times throughout the year. When three log-log plots of W, D, and V, against Q are graphed and linear analysis of a best fit line is performed, the hydraulic characteristics are seen as a simple power function of varying discharge such that:

$$W = a\,Q^{b}$$
$$D = c\,Q^{f}$$
$$\text{and } V = k\,Q^{m} \ldots$$

where coefficients a, c, and k represent the y-intercept of the line and exponents b, f, and m represent the slope of the line. Furthermore, from the continuity equation:

$$W * D * V = Q$$

it follows that:

$$a * c * k = 1$$

and:

$$b + f + m = 1$$

When working with hydraulic geometry, the exponent values are of greater importance and are used to compare one stream to another.

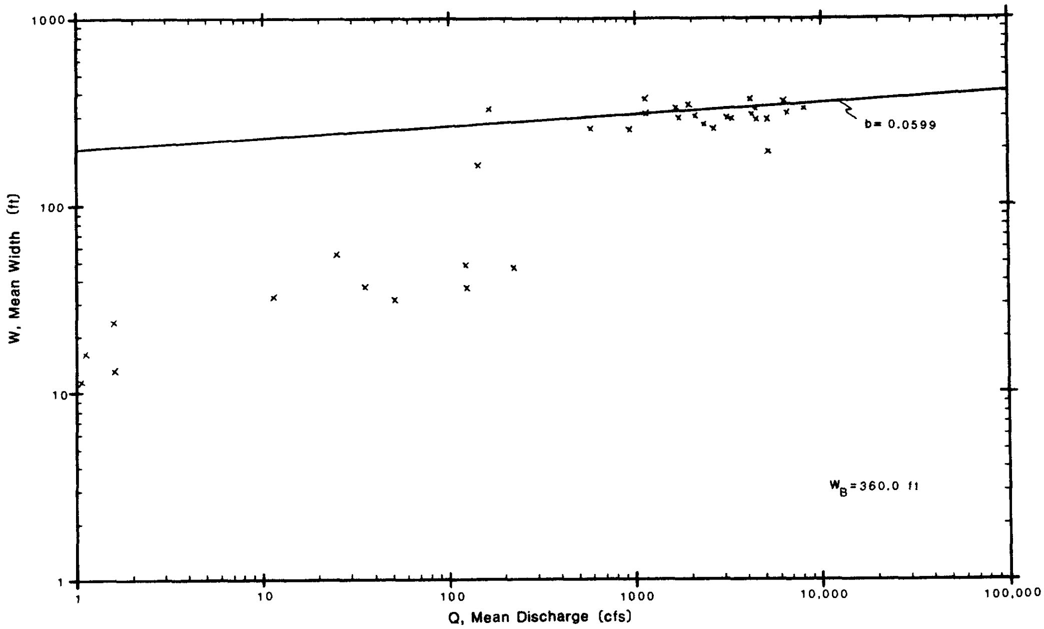
At the gaging station near Sagwon, information was collected for eight years, but not all of the information was used when determining the best fit line through the data on the plots of W, D, and V versus Q. Many of the surveys were conducted when the river was partially or completely covered by ice, and all data points where Q was less than 800 cfs (22.6 m^3/s) were suspected of some ice cover, as indicated by the field notes. The distribution of data points, for streamflow greater than 800 cfs falls on a fairly well defined line, whereas data points of lesser streamflow are quite scattered. For this reason, linear regression analysis was performed using only discharges above 800 cfs (Figures 5-7 and Table 2). The characterizing exponent values were b=0.06, f=0.46, and m=0.47. Using the same principles, linear regression analysis was performed at the Atigun tributary gaging station using only discharges above 10 cfs (0.28 m^3/s). The characterizing exponent values were b=0.13, f=0.17 and m=0.63 (Figures 8-10 and Table 3). In comparison, average values for the exponents at 158 gaging stations in the United States were b=0.12, f=0.45, and m=0.43 (Dunne and Leopold, 1978).

Emmett (1972) conducted hydraulic geometry surveys of Alaskan streams at 22 sites in the South-Central and Yukon hydrologic subregions. The mean values of exponents at these 22 sites were: b=0.19, f=0.39, and m=0.42. He discovered that although there was variability in individual stream values of b, f, and m, the values within a group of streams were rather consistent. Further studies of hydraulic geometry have yet to be conducted on other North Slope streams, to see if consistency exists here, also. The Atigun tributary and Sagwon data most closely approximate the data of the South-Central hydrologic region. The streams in this area drain into the gulf of Alaska, and have lower topographic relief (similar to the relief of the Sagavanirktok) than the streams of the Yukon hydrologic region, which are located much farther inland, at higher elevations. One important consideration must be noted in the comparison. The streams in the South-Central and Yukon regions have year-round stream flow, although winter flow is much lower, whereas the Sagavanirktok River virtually ceases to flow for eight to nine months out of the year.

Downstream from the Sagwon gaging station, four of the distributary channels (East Channel 1-3 and West Channel) at-a-station hydraulic geometry classification is much more difficult. Information must be obtained from the available cross-sections. Only a few known stages with known discharges are marked on each channel. The number of data points available for East Channels 1-3 and the West Channels are three, three, two, and four, respectively. Stage height and discharge values are given, but mean surface width and mean depth must be approximated using the scale provided on the cross-sections (Figures 11-14). With this uncertainty, velocity must be calculated by dividing discharge by depth times width. The information of W, D, and V, is plotted on log-log paper against Q and linear regression analysis is performed as before to determine b, f, and m values for each channel (Figures 15-18 and Table 4). There is a certain amount of absurdity associated with drawing a best-fit line through two data points, as in the case of East Channel 3, and a lack of confidence in the values

MEAN WIDTH VS. MEAN DISCHARGE

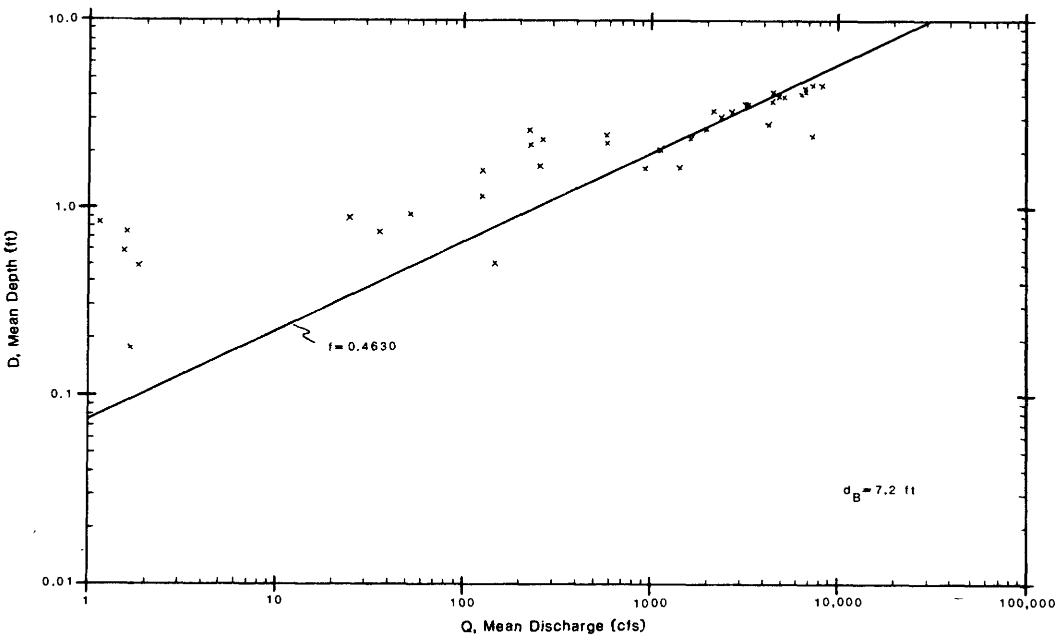
Sagavanirktok River at Sagwon, AK



-- FIGURE 5 --

MEAN DEPTH VS. MEAN DISCHARGE

Sagavanirktok River at Sagwon, AK



-- FIGURE 6 --

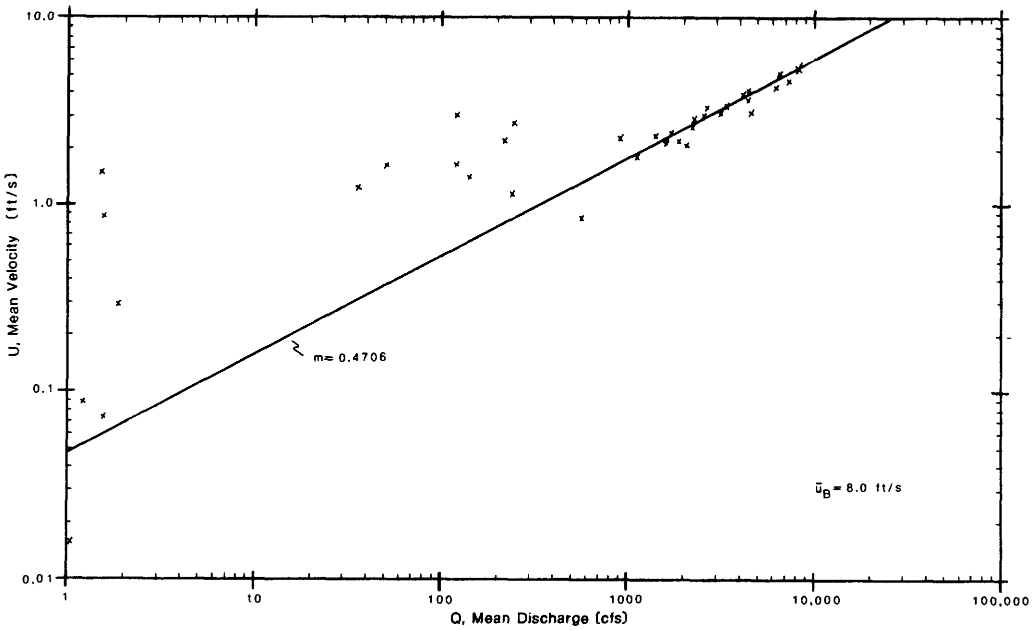
TABLE 2

USGS Gauging Station #15910000 -- Sagavanirktok River near Sagwon, AK. Information obtained from 9-207 forms: 1970-1978.

Date	Gauge Height (ft)	W Width (ft)	D Depth (ft)	A Area (ft^2)	V Velocity (ft/s)	Q Discharge (ft^3/s)
8-14-70	11.32	368.0	2.26	830.0	3.05	2,530.0
9-03-70	11.18	323.0	2.60	837.0	2.69	2,250.0
6-05-71	13.28	348.0	4.51	1,570.0	4.69	7,370.0
8-01-71	12.40	335.0	3.94	1,320.0	3.27	4,720.0
9-09-71	9.87	250.0	1.63	407.0	2.32	942.0
7-11-72	12.20	377.0	2.78	1,050.0	3.94	4,150.0
8-30-72	12.29	305.0	3.77	1,150.0	3.81	4,440.0
8-10-73	13.57	330.0	4.54	1,500.0	5.42	8,130.0
9-08-73	11.00	299.0	3.28	980.0	2.17	2,130.0
8-07-74	11.28	255.0	3.19	813.0	3.29	2,680.0
9-06-74	10.64	340.0	2.56	871.0	2.24	1,950.0
6-06-75	13.01	360.0	4.06	1,460.0	4.41	6,440.0
7-10-75	11.67	290.0	3.45	1,000.0	3.44	3,440.0
7-30-75	11.65	293.0	3.41	1,000.0	3.21	3,220.0
8-22-75	11.13	270.0	2.99	808.0	2.88	2,330.0
9-18-75	10.71	325.0	2.35	763.0	2.19	1,670.0
6-16-76	13.12	320.0	4.12	1,320.0	5.09	6,720.0
7-25-76	12.37	290.0	3.93	1,140.0	4.42	5,020.0
9-18-76	-	365.0	1.64	598.0	2.41	1,440.0
8-20-77	12.32	295.0	4.03	1,190.0	3.74	4,450.0
8-12-78	10.30	295.0	2.43	716.0	2.42	1,730.0
9-26-78	9.70	302.0	2.03	613.0	1.88	1,150.0

MEAN VELOCITY VS. MEAN DISCHARGE

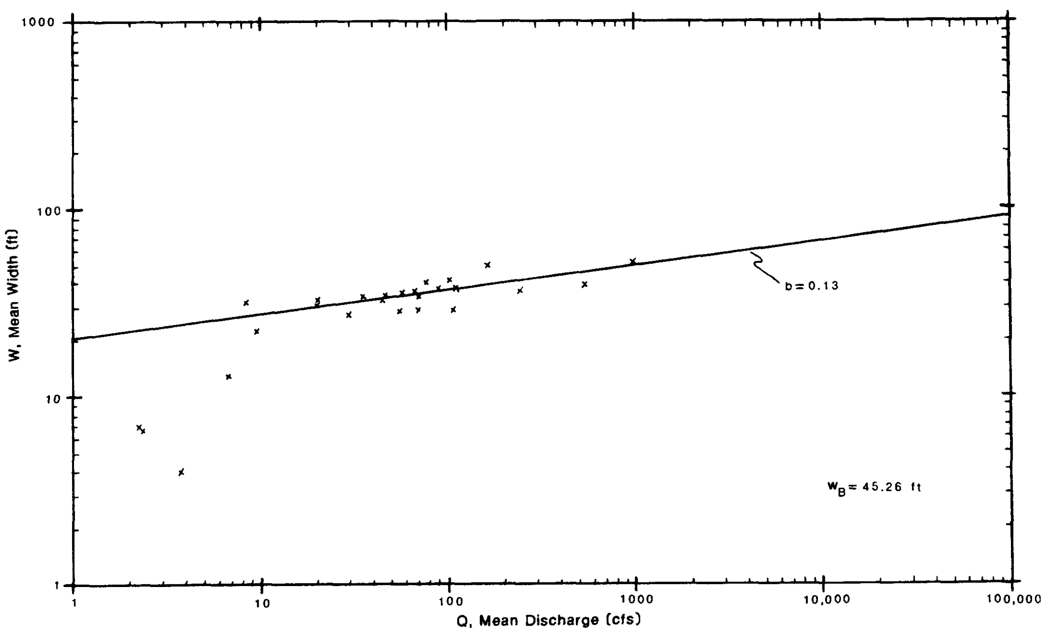
Sagavanirktok River at Sagwon, AK



-- FIGURE 7 --

MEAN WIDTH VS. MEAN DISCHARGE

Atigun River Tributary near Pump Station 4, AK



-- FIGURE 8--

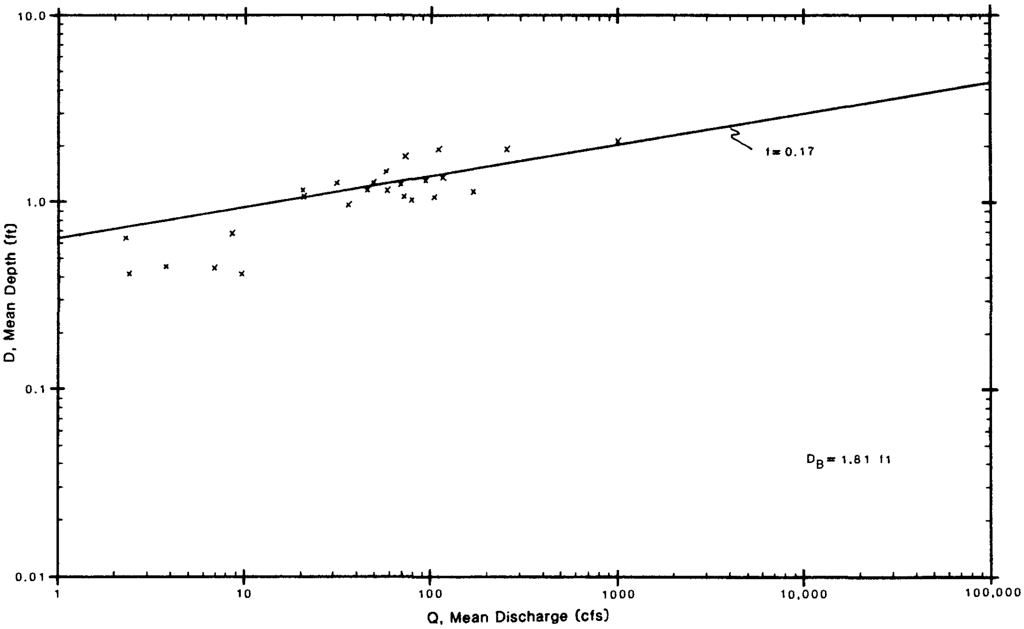
TABLE 3

USGS Gauging Station #15904900 -- Atigun River tributary to the Sagavanirktok River. Information obtained from 9-207 forms: 1977-1983.

Date	GH Gauge Height (ft)	W Width (ft)	D Depth (ft)	A Area (ft^2)	V Velocity (ft/s)	Q Discharge (ft^3/s)
6-09-77	12.34	36.0	1.97	70.9	3.54	251.0
7-20-77	10.93	28.0	1.45	40.6	1.40	56.6
8-20-77	11.38	42.0	1.05	44.0	2.39	105.0
8-20-77	11.40	28.5	1.92	54.7	2.02	110.0
6-05-78	11.02	34.5	1.09	37.7	1.88	70.9
8-12-78	10.75	34.0	0.96	32.7	1.11	36.3
6-28-79	10.96	36.0	1.11	40.1	1.47	59.2
8-14-79	11.46	37.0	1.38	50.9	2.20	112.0
8-15-79	11.08	35.0	1.22	42.8	1.61	69.1
9-13-79	10.48	32.0	1.09	34.8	0.58	20.2
6-04-80	10.65	27.0	1.23	33.2	0.91	30.3
7-19-80	11.35	37.0	1.32	48.7	1.89	92.2
6-17-81	11.94	50.0	1.12	55.9	3.02	169.0
8-12-81	11.18	40.0	1.05	41.8	1.89	79.1
6-16-82	10.91	33.0	1.14	37.7	1.21	45.6
7-30-82	11.02	33.0	1.26	41.6	1.19	49.4
9-03-82	10.57	30.8	1.18	36.3	0.57	20.8
8-02-83	11.21	29.0	1.77	51.3	1.39	71.3

MEAN DEPTH VS. MEAN DISCHARGE

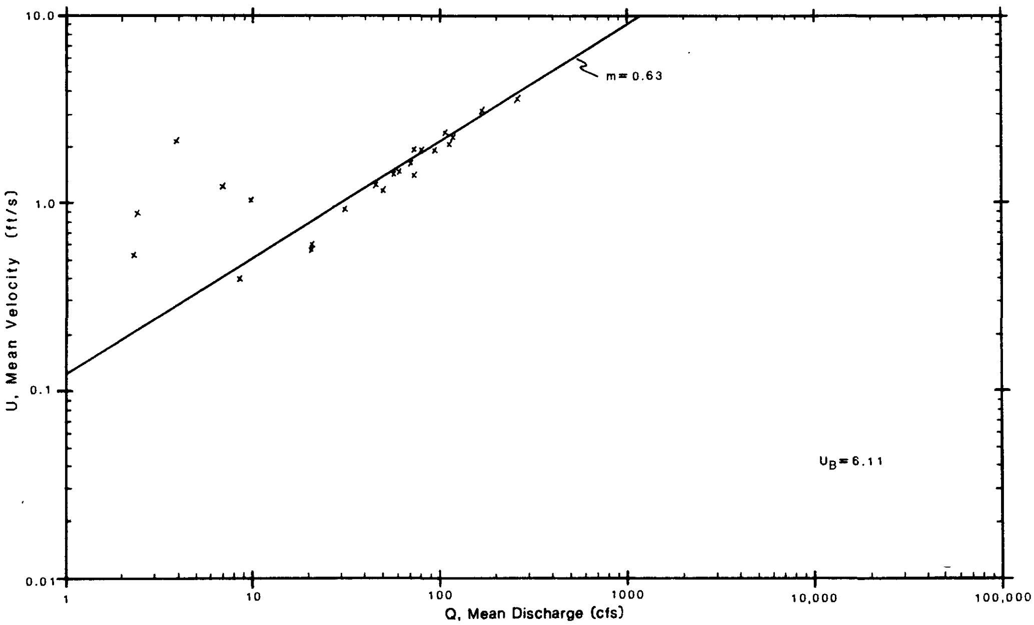
Atigun River Tributary near Pump Station 4, AK



-- FIGURE 9 --

MEAN VELOCITY VS. MEAN DISCHARGE

Atigun River Tributary near Pump Station 4, AK



-- FIGURE 10 --

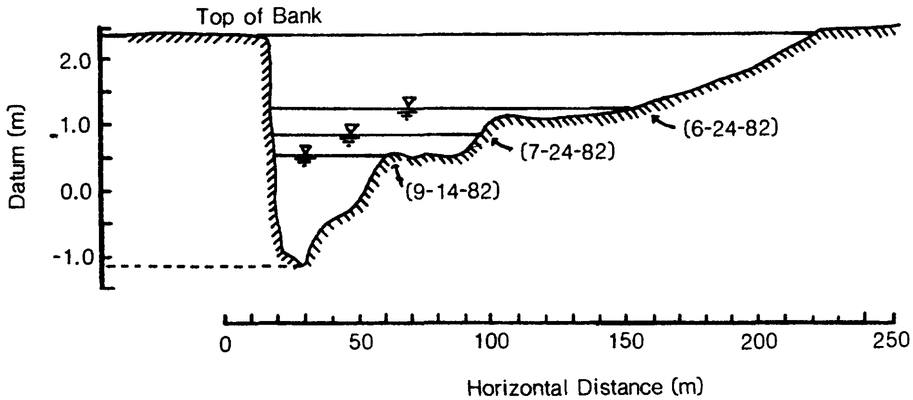


FIGURE 11 -- Cross section for East Channel #1 of the Sagavanirktok River (looking downstream). (Modified from Ecological Research Assoc., 1982)

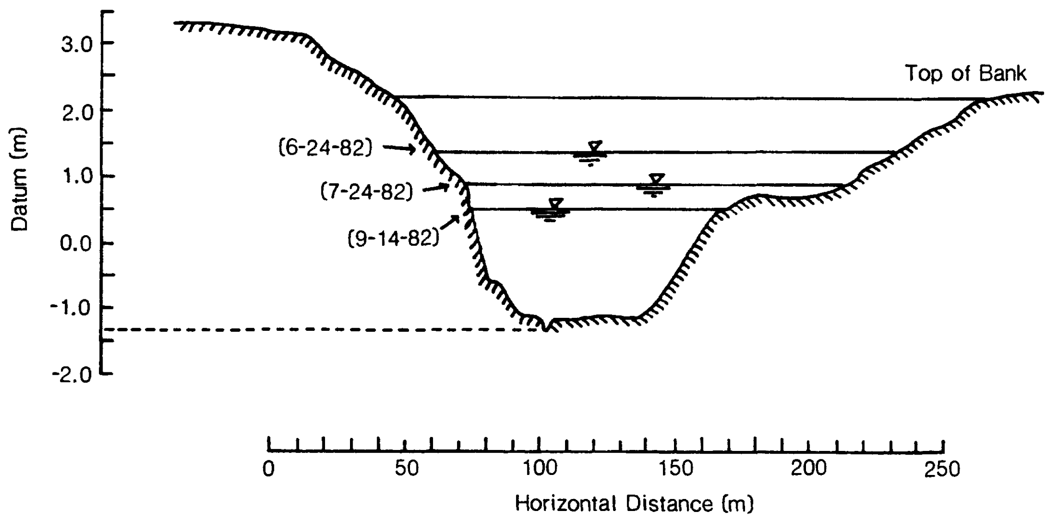


FIGURE 12 -- Cross section for East Channel #2 of the Sagavanirktok River (looking downstream). (Modified from Ecological Research Assoc., 1982)

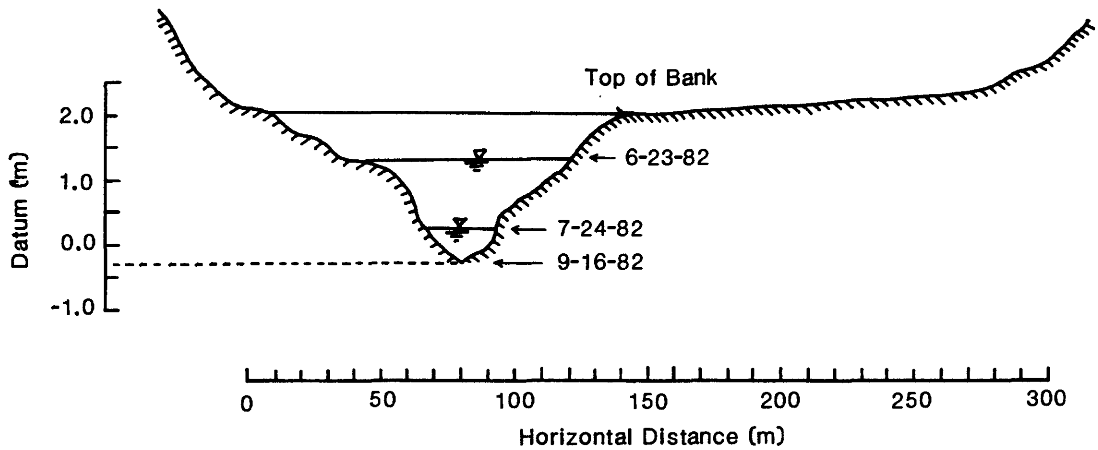


FIGURE 13 -- Cross section for East Channel #3 of the Sagavanirktok River (looking downstream). (Ecological Research Assoc., 1982)

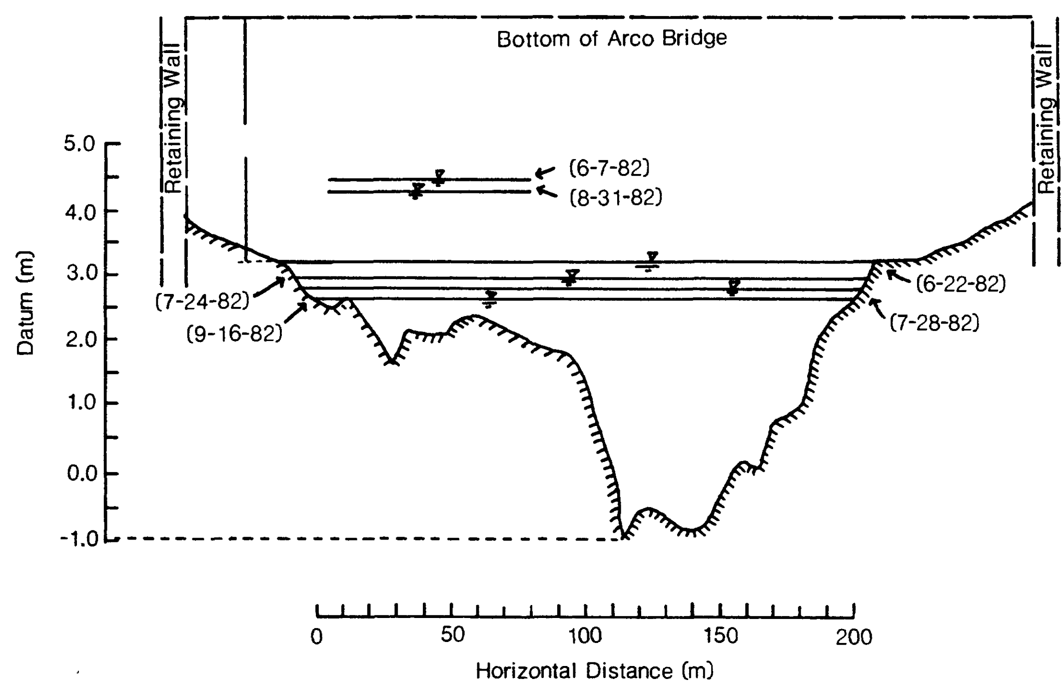
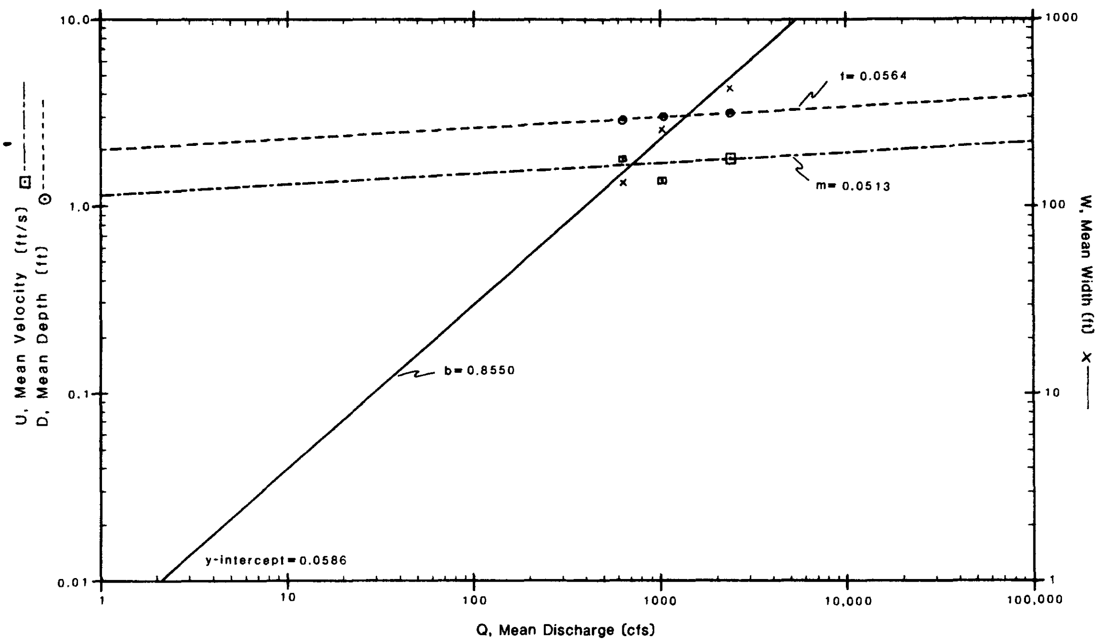


FIGURE 14 -- Cross section for the West Channel of the Sagavanirktok River (looking downstream). (Modified from Ecological Research Assoc., 1982)

HYDRAULIC GEOMETRY

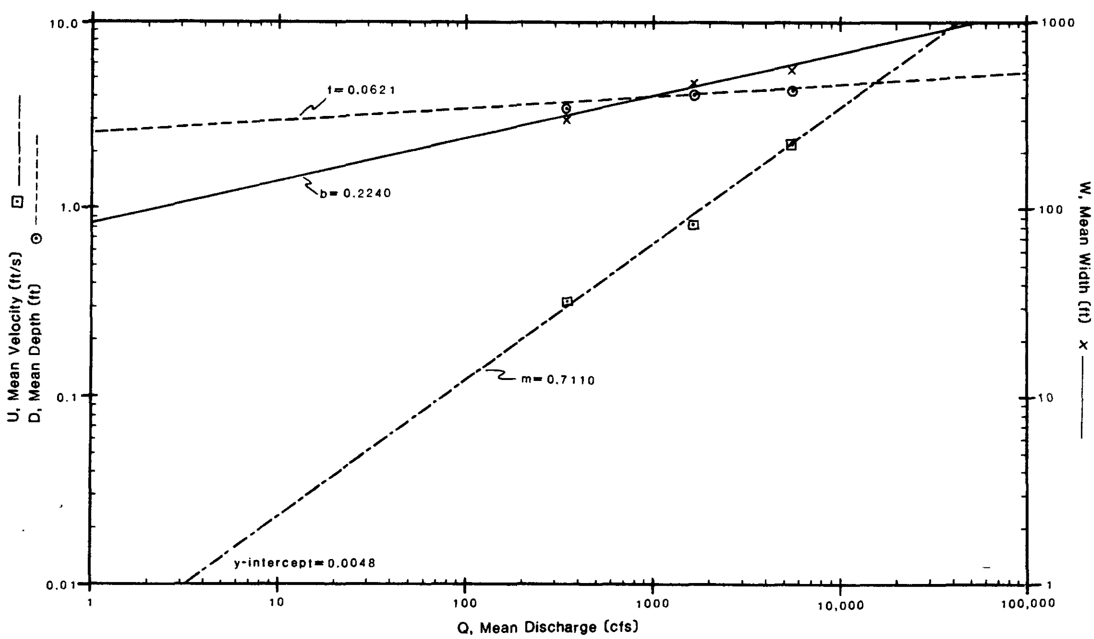
East Channel # 1, Sagavanirktok River Delta, AK



-- FIGURE 15 --

HYDRAULIC GEOMETRY

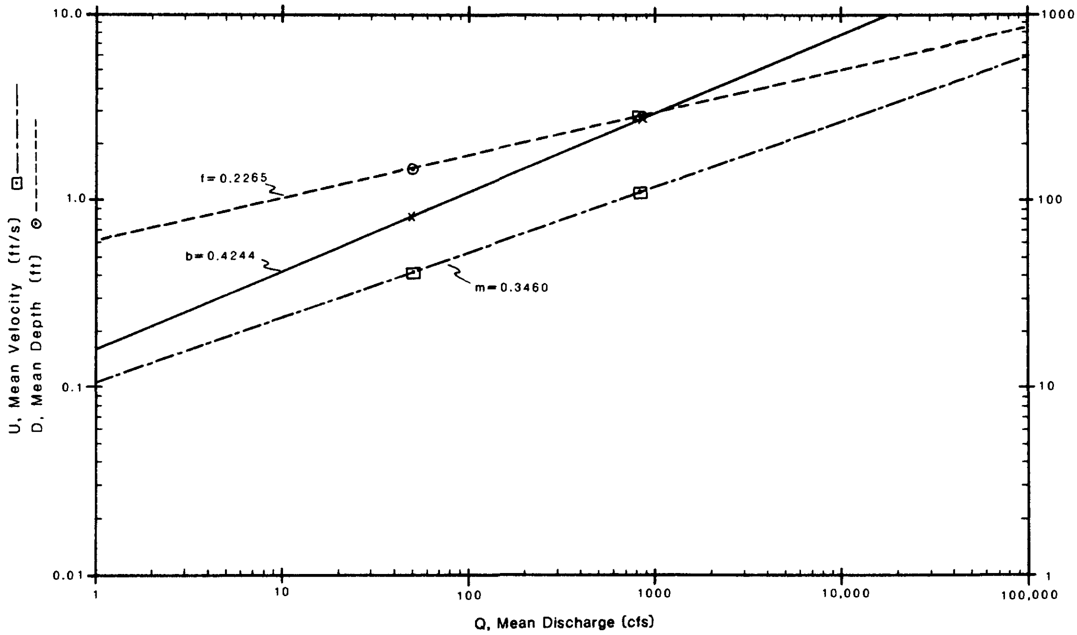
East Channel #2, Sagavanirktok River Delta, AK



-- FIGURE 16 --

HYDRAULIC GEOMETRY

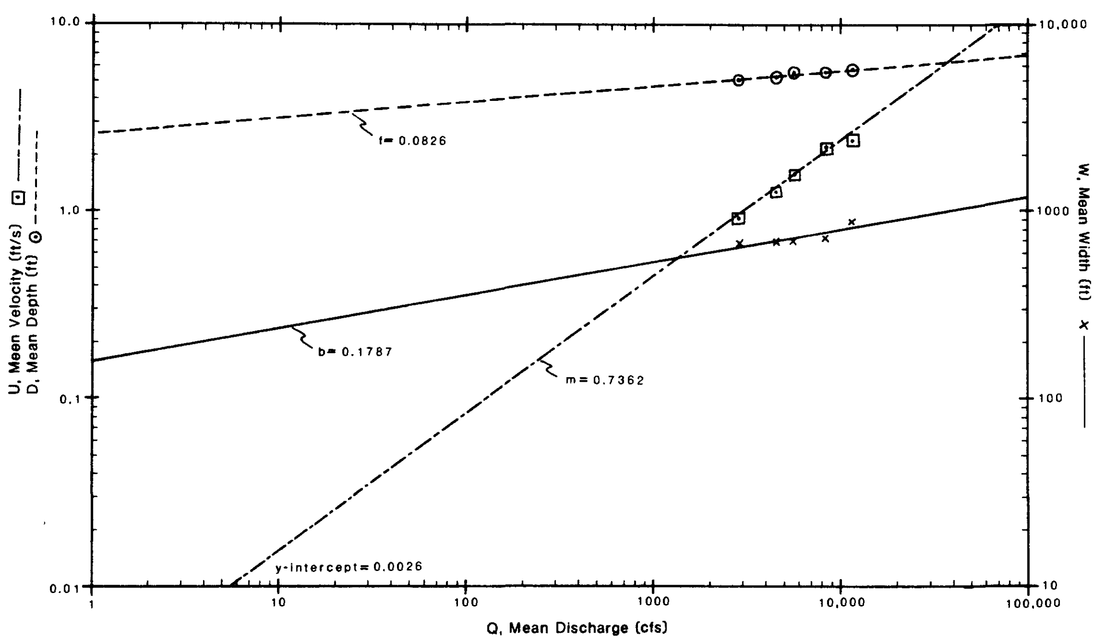
East Channel #3, Sagavanirktok River Delta, AK



-- FIGURE 17 --

HYDRAULIC GEOMETRY

West Channel, Sagavanirktok River Delta, AK



-- FIGURE 18 --

TABLE 4

Sagavanirktok River near Delta -- East Channels 1-3 and West Channel. Information obtained from cross-sections by Ecological Research Associates,1982.

Location/ Date	Gauge Height (ft)	W Width (ft)	D Depth (ft)	Q Discharge (ft^2)	u_{calc} Velocity (ft/s)
East Channel #1					
9-14-82	1.65	131.24	2.79	639.30	1.75
7-24-82	2.73	255.92	2.95	1,017.22	1.35
6-24-82	4.20	422.93	3.02	2,373.51	1.78
East Channel #2					
9-14-82	1.65	301.85	3.61	346.14	0.32
7-24-82	2.73	465.90	4.10	1,607.06	0.84
6-24-82	4.20	554.49	4.27	5,400.43	2.28
East Channel #3					
7-24-82	0.80	82.03	1.48	49.45	0.41
6-25-82	4.20	269.04	2.79	812.36	1.08
West Channel					
9-16-82	8.60	656.20	4.92	2,896.24	0.90
7-28-82	9.19	682.45	5.09	4,415.00	1.27
7-24-82	9.61	692.29	5.25	5,580.56	1.54
6-22-82	10.50	711.98	5.41	8,335.52	2.16
-	11.48	869.47	5.48	11,196.44	2.35

obtained when three and four data points are used. Unlike the Atigun and Sagwon exponents, the distributary hydraulic geometry is based on such scanty information that high variability exists in b, f, and m values. For East Channel 1: b=0.86, f=0.06, and m=0.05; East Channel 2: b=0.22, f=0.06, and m=0.71; East Channel 3: b=0.42, f=0.23, and m=0.35; and for the West Channel: b=0.18, f=0.08, and m=0.74. Distributary exponent determination seems to be of little value because the best-fit lines are based on such limited data and because few comparative hydraulic geometry studies have been conducted on distributary channels.

Channel Geometry:

One common way to analyze a stream channel is to look at the channel geometry. It has been assumed that river channels "are shaped by, and to accommodate, a dominant discharge" (Emmett, 1975). Dunne and Leopold (1978) suggest that bankfull stage, the stage when the stream just begins to top its banks and overflow the adjacent active flood plain, is representative of this dominant discharge.

Bankfull discharge may best be approximated by constructing a flow frequency series in which all known instantaneous maximum annual flows are ranked from highest to lowest, and then assigned a recurrence interval, T, such that:

$$T = \frac{n+1}{m}$$

where n = number of entries and m = the rank of the discharge. The annual maximum discharge is then plotted on probability paper against the recurrence interval. Bankfull has been determined to occur in most rivers with a recurrence interval of approximately 1.5 years, so the discharge at this point can be readily determined from the graph (Dunne and Leopold, 1978). The bankfull discharge at the Atigun tributary gaging station was found to be approximately 545 cfs (15.4 m^3/s). Further downstream at the Sagwon gaging station, bankfull discharge was found to be approximately 17,300 cfs (490 m^3/s) (Figures 19-20).

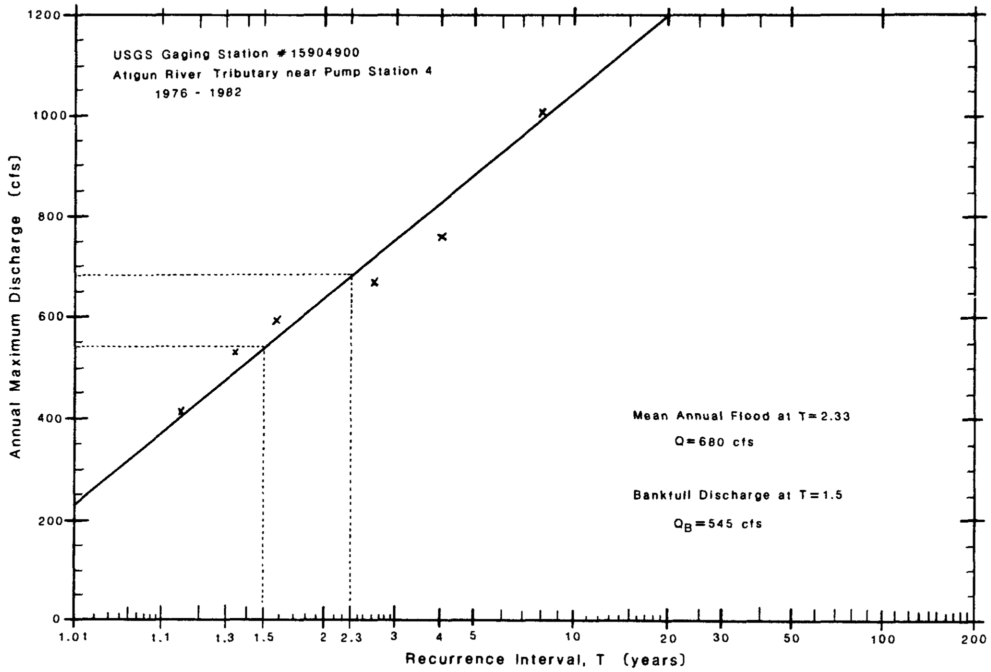
The determination of bankfull discharge cannot be made for the delta distributaries, using the flow frequency method, since no measurements of maximum instantaneous discharge are available. Approximations had to be made based on cross-sectional surveys where discharge was determined by estimating the width from bank to bank at the active flood plain, and the average depth at this width. This information was then used in looking up the corresponding discharge values on the at-a-station curves for each channel. This approach was only crudely successful in the three East channels, but location of heavy concrete retaining walls of the Arco bridge made bankfull determination impossible along the West Channel. Crude approximations of bankfull for East Channels 1 through 3 are: 3,200 cfs (90 m^3/s), 13,000 cfs (368 m^3/s), and 1,300 cfs (37 m^3/s) respectively. Assuming that these values are merely estimates, based on scanty information, and assuming that bankfull stage is reached in late May or early June when the West Channel carried 49% of the flow, we may make an even cruder estimate of Q_B=35,000 cfs (990 m^3/s) for the West Channel.

One trend can be seen without guessing at values. There is a downstream increase in the bankfull width/depth ratio of the stream near Sagwon to the distributary channels. The width at Atigun tributary is 50 times its depth, but at the distributary, the ratio is nearly two to three times larger. This latter ratio seems quite high, but actually is similar to ratios of other braided stream distributaries (Leopold, 1984; personal communication).

Sediment Transport:

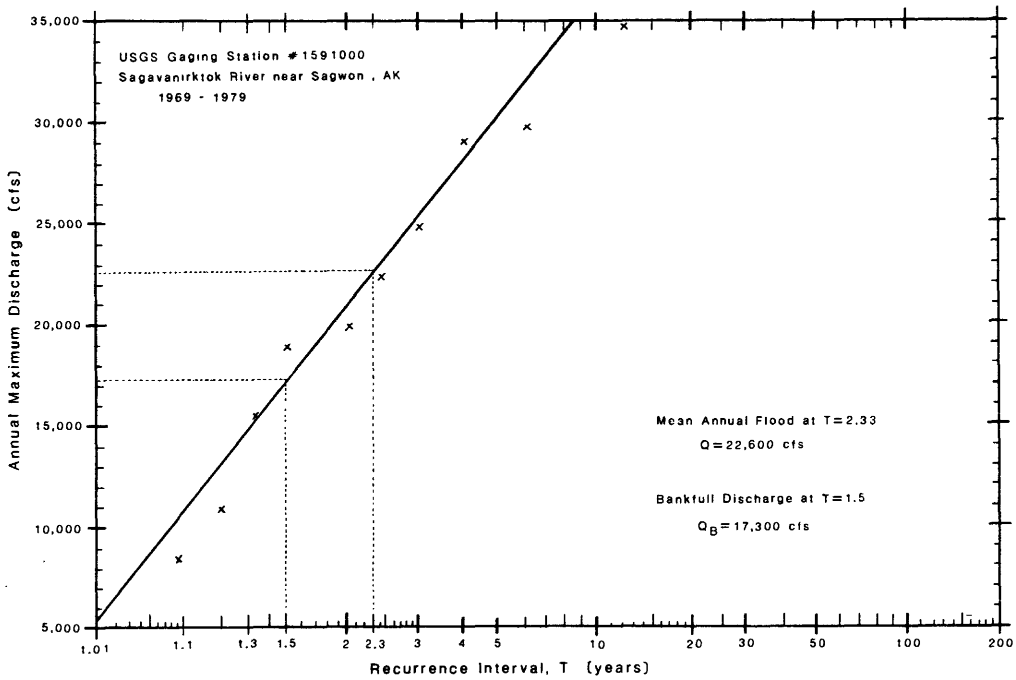
Estimates concerning contributions of North Alaskan river sediment to the ocean were recently published by Milliman and Meade (1983). They suggest that the suspended sediment discharge is ~ 42 x 10^6 t/yr, compared to the world-wide total of ~ 13.5 x 10^9 t/yr. Few such studies have been

FLOOD FREQUENCY CURVE
Atigun River Tributary near Pump Station 4, AK



-- FIGURE 19 --

FLOOD FREQUENCY CURVE
Sagavanirktok River near Sagwon, AK



-- FIGURE 20 --

conducted on North Slope streams, but using discharge and channel geometry data from gaging stations, crude estimates of sediment bedload transport may be made.

Bedload

Boothroyd et al. (1983), have stated that the Sagavanirktok River is degradational for most of its length, and is only aggradational for the last 20 km (12.5 mi). Many workers have observed that little or no bedload is currently being carried onto the Beaufort Sea shelf (Reimnitz, 1984; personal communication). This suggests that the river may be aggradational for a longer distance. With discharge and channel geometry data from the gaging stations near Sagwon and the four distributary channels, crude estimates of bedload may be calculated. The Atigun tributary was omitted from this analysis because its drainage area, and therefore sediment yield, are insignificant compared to that of the total drainage basin. One major assumption in the bedload estimates is crucial to the calculations: the boundary shear stress, T_b, is assumed to be equal to the critical shear stress, T_c, at bankfull, determined to be the time of maximum channel change.

The most reliable bedload calculations may be made from the station which has the most extensive hydrologic data, in this case, the reach of river near the Sagwon gaging station. The slope here was determined to be 0.0029, based on longitudinal profile surveys conducted by the USGS Water Resources Division. Bankfull discharge, Q_B, was determined to be 490 m^3/s or 17,300 cfs. At bankfull depth (D_B=2.2 m or 7.2 ft), T_b was estimated to be 624.3 dynes/cm^2 and shear velocity, u_*, was estimated to be 25.0 cm/s. Using this information in the following equation:

$$u = u_* \left[\frac{1}{k} \ln \frac{11h}{3.49\, D_{84}}\right]$$

where u represents velocity, k represents von Karmen's constant, and h represents depth, D_{84} was calculated to be 131 mm at bankfull. The D_{84} value means that 84% of the grains are smaller than this value. Since the D_{84} value of particles on a gravel stream bed is considered to be nearly double the median grain diameter, D_{50}, value (Klingeman and Emmett, 1982) this information is in keeping with the interpolation of D_{50}, using information by Scott where D_{50}=65 mm. Calculations of bedload were determined using the Bagnold-Leopold-Emmett curves of unit stream power, w (kg/m x s), versus unit bedload transport rate by immersed weight, i_b (kg/m x s). Bedload transport, Q_S, for a 110 m (360 ft) bankfull width was 3.32 x 10^{-3} m^3/s. If two days were used to approximate the time period of maximum flow, based on information contained on the hydrographs, then the bedload sediment yield is calculated at 1.50 x 10^3 t/yr or 0.26 t/yr per km^2 of drainage area. Both estimates show a very low annual yield when compared to Milliman and Meade's estimate of 120 t/km^2/yr suspended sediment yield for North Alaskan streams (Milliman and Meade, 1983).

Information involving bankfull determinations at the distributary channels are crude estimates. Therefore, calculations for bedload transport are also crude estimates. The slope of the river was not given in the reports and was too gradual to be obtained using a topographic map. Scott's distributary slope value of 0.00053 was used as the best possible approximation. It was assumed that the best approximation for D_{50} would be that observed by Scott at the distributary, D_{50} = 15 mm. Using the Bagnold-Leopold-Emmett curves for bedload calculation of the East Channels, there is no bedload transport. This is in keeping with the previous observations that at the river distributary, little or no bedload sediment is transported to the sea.

Suspended Load

Suspended sediment transport occurs for a longer period of time than does bedload transport. During the winter there is no measurable suspended sediment contributed from surface drainage. During the spring, when water first begins to form on the ice surface, there is still no suspended sediment because the permafrost cements the surficial materials, and the river ice protects the river bed materials. As thaw progresses, the permafrost is melted to a few meters, and the bottom ice works itself loose in the river. Suspended sediment concentrations increase at this time and continue to increase with rising stage. As stage decreases, suspended sediment is deposited on top of ice, river banks, and mudflats, but may be re-released as ice breaks up and river banks slump into the river (Arnborg et al., 1967).

No measurements of yearly suspended sediment discharge have been made along the Sagavanirktok delta channels, but the amount of suspended sediment discharged soon after the peak flow in early June has been measured (Sagwon has nearly 2,500 t/day and the West Channel has nearly 7,000 t/day). This information shows that the amount of suspended sediment transported is considerably greater than the amount of bedload transported.

CONCLUSION

The Sagavanirktok River has been characterized by its channel morphology, streamflow, and sediment bedload. Its drainage basin receives low precipitation and streamflow is concentrated during a short summer period of thawing of snow cover and frozen ground and streams. The Sagavanirktok River has several additional stream processes which affect streamflow and sediment transport and differentiates it from other streams. These are the arctic phenomena of permafrost, icings and frazil ice/anchor ice. All have a unique effect on channel morphology, river hydrology and sediment transport in this North Slope desert environment.

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REFERENCES

Arden, R.S. and Wigle, T.E., 1973, Dynamics of ice formation in the Upper Niagra River: Int. Symp. on the Role of Snow and Ice in Hydrology, Banff, Alberta, 1972; v. 2, p. 1296-1313.

Arnborg, L., Walker, H.J., and Peippo, J., 1966, Water discharge in the Colville River, 1962: Geografiska Annaler, v. 48A, p. 195-210.

Arnborg, L., Walker, H.J., and Peippo, J., 1967, Suspended load in the Colville River, Alaska, 1962: Geografiska Annaler, v. 49A, p. 131-144.

Beikman, H.M. and Lathram, E.H., 1976, Preliminary map of Northern Alaska: USGS Map File #789, 2 sheets.

Boothroyd, J.C. and Timson, B.S.,1983, The Sagavanirktok and adjacent river systems, eastern North Slope, Alaska: An analog for ancient fluvial terrain on Mars; in Permafrost: Proceedings of Fourth International Conference, National Academy Press, Washington D.C., p. 74-79.

Carey, K.L., 1973, Icings developed from surface water and ground water: U.S. Army Cold Regions Research and Engineering Laboratory, Cold Science and Engineering Monograph III-D3.

Childers, J.M., Sloan, C.E., Meckel, J.P. and Nauman, J.W., 1977, Hydrologic reconnaissance of the eastern North Slope, Alaska, 1975: USGS OF Rept. #77-492, 65 p.

Drage, B., Gilman, J.F., Hoch, D. and Griffiths, L., 1983, Hydrology of North Slope coastal plain streams; in Permafrost: Proceedings of Fourth International Conference, National Academy Press, Washington D.C., p. 249-254.

Dunne, T. and Leopold, L.B., 1978, Water in environmental planning: San Francisco, W.H. Freeman and Co., 552 p.

Ecological Research Associates, 1982, Sagavanirktok River: Hydrology and hydraulics; Environmental Summer Studies (1982) for the Endicott Development, Vol. II, p. 31-43.

Emmett, W.W., 1972, The hydraulic geometry of some Alaskan streams south of the Yukon River: USGS OF Rept, 102 p.

Emmett, W.W., 1975, The channels and waters of the upper Salmon River area, Idaho: USGS Prof. Paper 870-A, 116 p.

Harden, D., Barnes, P. and Reimnitz, E., 1977, Distribution and character of naleds in northeastern Alaska: Journal of the Arctic Institute of North America, v. 30, p 28-40.

Keller, A.S., Morris, R.H. and Detterman, R.L., 1961, Geology of the Shaviovik and Sagavanirktok Rivers region, Alaska: USGS Prof. Paper 303-D, 222 p.

Klingeman, P.C. and Emmett, W.W., 1982, Gravel bedload transport processes; in Hey, R.D., Bathurst, J.C. and Thorne, C.R. (Eds.), Gravel-Bed Rivers, John Wiley & Sons Ltd., p. 141-178.

Kvisigild, H.R., 1970, River and lake ice terminology: International Association of Hydraulic Research, Paper 1.0, 14 p.

Martin, S., 1981, Frazil ice in rivers and oceans: Ann. Rev. Fluid Mech., v. 13, p. 379-397.

Milliman, J.D. and Meade, R.H., 1983, Worldwide delivery of river sediment to the oceans: Jour. Geology, v. 91, p. 1-21.

Osterkamp, T.E., 1977, Frazil-ice nucleation by mass-exchange processes at the air-water interface: Jour. of Glaciology, v. 19, p. 619-625.

Scott, K.M., 1978, Effects of permafrost on stream channel behavior in arctic Alaska: USGS Prof. Paper 1068, 19 p.

Slaughter, C.W., Hilgert, J.W. and Culp, E.H., 1983, Summer streamflow and sediment yield from discontinuous-permafrost headwater catchments: in Permafrost: Proceeding of Fourth International Conference, National Academy Press, Washington D.C., p. 1172-1177.

Sloan, C.E., Zenone, C. and Mayo, L.R., 1976, Icings along the Trans-Alaska Pipeline route: USGS Prof. Paper 979, 32 p.

U.S. Geological Survey, 1978, Water resources data for Alaska Water Year 1977: USGS Water Data Rept. AK 77-1, 439 p.

Wahrhaftig, C., 1965, Physiographic divisions of Alaska: USGS Prof. Paper 482, 52 p.

Walker, H.J., 1973, Morphology of the North Slope: in Alaskan Arctic Tundra, M.E. Britton (Ed.), Arctic Institute of North America, Tech. Paper #25, p. 49-92.

Walker, H.J., 1974, The Colville River and Beaufort Sea: Some interactions; in Reed, J.C. and Sater, J.E. (Eds.), The Coast and Shelf of the Beaufort Sea: Arlington, Virginia: Arctic Institute of North America, P. 513-540.

Walker, H.J., 1983, Erosion in a permafrost dominated delta, in Permafrost: Proceedings of Fourth International Conference, National Academy Press, Washington D.C., p. 1344-1349.